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14. ABSTRACT The last decade has seen a dramatic increase in computational power and sensor ubiquity, as well as an ever increasing demand for finer resolution in both scientific and geometric modeling. This has led to the creation of enormously large data sets with exquisite detail. However, these data sets will be useful only if we can process them efficiently, whether it be for storage, transmission, visual display, fast on-line graphical query, correlation, or registration against data from other modalities. Raw data sets are typically inaccessible and need to be transformed to more efficient representations for further processing. Several competing issues emerge. Sparsity is essential for efficient transmission, storage, and computation. Multiscale representations are critical to extract features at desired scales. Implementation in silicon leads to new issues of robustness in the face of computational error and imprecise circuit implementation. An emerging technology to address these issues utilizes redundant representations. High oversampling followed by coarse quantization is the preferred method for analog to digital conversion of signals. Sparse representation of images using redundant families of waveforms is effectively utilized in feature extraction and denoising. These redundant families can be frames, dictionaries, or libraries of bases. On the other hand, there is, at present, no compelling theory to explain the advantages of redundancy in image and signal processing. This program will convene leading experts from data representation into two workshops to describe the current understanding of the benefits of redundancy and to set forward a program for further research.

15. SUBJECT TERMS
Sparsity; Multiscale representations; computational error; imprecise circuit implementation; redundant representations; high oversampling ; coarse quantization; digital conversion of signals; sparse representation of images ; waveforms.

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Report on CSCAMM workshops on Sparse Representation:

Oversampling and Coarse Quantization for Signals, April 11-15, 2005 and Sparse Representation in Redundant Systems, May 9-13, 2005

Much emphasis of the workshops was placed on the idea of compressed sensing. It was recently discovered by several researchers (primarily Candes and Donoho) that probabilistic methods can be used to generate a sequence of k vectors in Euclidean n-dimensional space with the following remarkable property. The inner products of any signal vector with these k vectors produce k numbers which completely determine the signal vector whenever it is sparse (that is has small support). These ideas may lead to the construction of new super sensors. Many talks were concerned with refining these results and discussing how the signal vector can be captured from this inner product information.

Below we itemize the open problem and mathematical challenges that emerge from the two CSCAMM workshops.

Three main questions were identified to clarify and improve these results:

1. Are there deterministic constructions for the k vectors which are numerically stable. Daubechies and Varakh showed it is possible to use results from error correcting codes to make determinimistic constructions of the k vectors but these constructions are not known to be numerically stable.

2. Are there quantitative versions of this theory which would clarify the accuracy in representation that would occur when the signal vectors is not sparse? Current results of this type do not seem to be definitive.

3. What are the most effective and numerically friendly methods to recover the signal vector from these k inner products?
The two competing technologies are (i) l1 minimization via linear programming and (ii) greedy algorithms.

Several other groundbreaking areas were introduced. One of these was anisotropic spaces (DeVore and Dekel) to measure when functions have sparse representations. Spaces were defined via level sets but for limited smoothness orders.

4. What are the correct analytical measures of smoothness via level sets which would measure smoothness of arbitrary orders?
Two leading possibilities are to use evolution equations or interpolation of sets.

Another major topic of the workshop was the use of frames rather than bases for sparse representations.

5. What is the tradeoff between the redundancy in the frame and the gain in sparseness of the representation of a signal?

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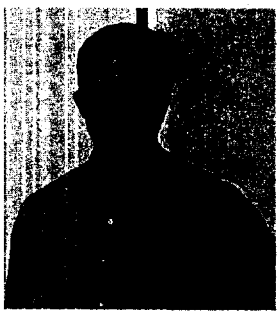

Decoding by Linear Programming and Other Perhaps Surprising Phenomena

Dr. Emmanuel Candes

Applied / Computational Mathematics at California Institute of Technology

Abstract: Suppose we wish to transmit an n-dimensional vector f (the ``plaintext'). We generate another m-dimensional vector Af (the ``ciphertext') where A is an m by n matrix with m > n which is to be sent. A recurrent problem with real communication or storage devices is that some of the entries of the ciphertext may become corrupted; the corrupted entries are unreliable and may have nothing to do with the original values. We do not know which entries are affected nor do we know how they are affected. We will show that no matter what the corruption is like, it is provably possible to recover the original message by solving a convenient linear program (provided that the fraction of corrupted entries is not excessively large). This work is related to the problem of finding sparse solutions to vastly underdetermined systems of linear equations. I will discuss these significant connections and introduce a new collection of results showing that it is possible to recover sparse or compressible signals accurately, and sometimes even exactly, from highly incomplete measurements. Parts of this work are joint with Terence Tao and Justin Romberg.

[LECTURE SLIDES]

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On Greedy Algorithms with Restricted Depth Search[1]

Dr. Vladimir Temlyakov

Department of Mathematics, University of South Carolina

Abstract: We continue to study effeciency of approximation and convergence of greedy type algorithms in uniformly smooth Banach spaces. This talk is based on a development of recent results in the direction of making practical algorithms out of theoretical approximation methods. The Weak Chebyshev Greedy Algorithm (WCGA) is a general approximation method that works well in an arbitrary uniformly smooth Banach space X for any dictionary D. It is an inductive procedure with each step of implementation consisting of several substeps. We describe the first substep of a particular case of the WCGA. Let $t \in (0, 1]$. Then at the first substep of the mth step we are looking for an element φ_m from a given symmetric dictionary D satisfying

(1) $$F_{f_{m-1}}(\varphi_m) \geq t \sup_{g \in D} F_{f_{m-1}}(g)$$

where f_{m-1} is a residual after $(m-1)$th step and $F_{f_{m-1}}$ is a norming functional of f_{m-1}. It is a greedy step of the WCGA. It is clear that in the case of infinite dictionary D there is no direct computationally feasible way of evaluating $\sup_{g \in D} F_{f_{m-1}}(g)$. This is the main issue that we address in the talk. We consider countable dictionaries $D = \{\pm\psi_j\}_{j=1 \text{ to } \infty}$ and replace the inequality used above by

$$F_{f_{m-1}}(\varphi_m) \geq t \sup_{1 \leq j \leq N_m} | F_{f_{m-1}}(\psi_j)|, \ \ \varphi_m \in \{\pm\psi_j\}_{j=1 \text{ to } N_m}$$

The restriction $j \leq N_m$ is known in the literature as the depth search condition. We prove convergence and rate of convergence results for such a modification of the WCGA.

[1]This research was supported by the National Science Foundation Grant DMS 0200187

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Signal Recovery from Partial Information via Orthogonal Matching Pursuit

Dr. Joel Tropp

University of Michigan at Ann Arbor

Abstract: This talk will demonstrate theoretically and empirically that a greedy algorithm called Orthogonal Matching Pursuit (OMP) can reliably recover a signal with m nonzero entries in dimension d given $O(m \ln d)$ random linear measurements of that signal. This is a massive improvement over previous results for OMP, which require $O(m^2)$ measurements. The new results for OMP are comparable with recent results for the Basis Pursuit (BP) algorithm. The OMP algorithm is much faster and much easier to implement, which makes it an attractive alternative to BP for signal recovery problems.

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Randomness and Determinism in Sparse Algorithms

Dr. Ingrid Daubechies & Dr. Vahid Tarokh

(Princeton University & Harvard University)

Abstract: Supersparse algorithms (see the talks by Gilbert, Tropp, Zou on Tuesday in this workshop) rely on randomness, both in the construction of the "measurement matrix" and in the algorithm that reconstructs the sparse underlying vector from the measurements, and they prove that the desired sparse decomposition or approximation is obtained with high probability. Donoho, Candés & Tao, Rudelson & Vershynin (see the talks on Monday in this workshop) have shown that when l^1-minimization algorithms are used (which are not super fast), the measurement matrix need not be random: they prove that there exist (increasingly
frequently among random choices as the dimension N increases) K x N matrices H, with K < N, such that arbitrary M-sparse vectors v (i.e. $v \in C^N$ or R^N, with $\#\{n;v_n \neq 0\} \leq M$; $M < K$, with typically $K = O(M \log N)$) can be recovered completely from $y = H_v$ by l^1 - minimization: $v = \mathrm{argmin}_u\{\|u\|_{l^1};H_u = y\}$. However, so far no explicit constructions of such matrices H are known - the existence arguments are probabilistic.
In this talk two different approaches will be sketched that construct explicit measurement matrices H, using results and techniques from coding theory. The recovery algorithms are not l^1-based.

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CAMP: Extremely Local MR Representations

Dr. Amos Ron

Computer Sciences at University of Wisconsin at Madison

Abstract: We introduce a new type of wavelet-like representation, dubbed CAMP (Compression-Alignment-Modified Prediction). The hallmarks of CAMP are:
(1) Universal: the methodology works at all spatial dimensions, and for all dilation (i.e., decimation) processes.
(2) Simple: The algorithm is simple, and requires the user to merely select 2-3 low-pass filters and 0-1 full-pass ones (the simplest variant of the algorithm, thus, requires 2 low filters, and the most sophisticated variant requires 3 low-pass filters and one full-pass). One of these filters is 1D and should be interpolatory. There is no further restriction on the selection of the filters. (But, as must be expected, the performance of the representation hinges on certain properties of those filters.)
(3) Fast: Much like standard wavelet constructions, the decomposition and reconstruction are done by a fast algorithm with linear complexity.
(4) Rigorous: Much like in standard wavelet constructions, the representation is associated with performance grade, which is related to the function space characterizations ordered by the representation.
(5) Extremely local: In sharp contrast with mainstream wavelet representations and/or pyramidal representations, the CAMP representation is extremely local. In fact, *the number of operations R that is required for computing one cycle of decomposition- reconstruction satisfies a bound $R \le CNR_0/\Lambda$, with R_0 the tap (= number of non-zero coefficients) in one of the low-pass filters, with Λ the determinant of the dilation process (i.e., $\Lambda = 2^n$ for dyadic decimation in n dimensions), with N the size of the dataset, and with $C \approx 3$ a small constant that is independent of the type of decimation used, as well as of the spatial dimension*.

We capture the performance of the new representation in the two standard ways: (i) in the ability to provide Jackson-type estimates for functions of a given smoothness, and (ii) in the (more demanding) ability to characterize completely the smoothness class of the function in terms of the detail coefficients of the representation. The performance analysis is accomplished by recasting the representation in terms of a framelet, and explicitly finding a formula for the dual framelet. That dual framelet is used only for the analysis of performance: the reconstruction algorithm based on it will have a catastrophic complexity.

As an illustration of the *extreme locality* property, we compare the tensor-product biorthogonal 7/9 to one of our CAMP representations that has similar performance. In 3D, the above-mentioned 7/9 uses a total of 8 filters with an average of 512 taps. Our CAMP uses (implicitly, since the high-pass filters are never constructed) a total of 9 filters, with an average size of 18 taps per filter. In 4D, the 7/9 involves 4096 taps per filter. Our CAMP involves a mere 41 coeffecients per filter.

The specific details of this CAMP representation and its reconstruction algorithm indicates that the principles for effecient encoding of the representation should be quite different from those that are employed in wavelet representations.

This is a joint work with Youngmi Hur, a graduate student at UW-Madison.

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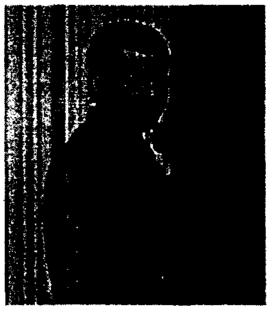

Density, Overcompleteness, and Localization of Frames

Dr. Christopher Heil

Mathematics at Georgia Institute of Technology

Abstract: We present a quantitative framework for describing the overcompleteness of a large class of frames. We introduce notions of localization and approximation between two frames $F = \{f_i\}_{\{i \text{ in } I\}}$ and $E = \{e_j\}_{\{j \text{ in } Z^d\}}$, relating the decay of the expansion of the elements of F in terms of the elements of E. A fundamental set of equalities are shown between two seemingly unrelated quantities: the relative measure, which is determined by certain averages of inner products of frame elements with their corresponding canonical dual frame elements, and the density of the index set I. The above equalities lead to an array of new results that hold for general localized frames. When applied to irregular Gabor frames these recover the Nyquist density theorems as well as giving new results, including relations between frame bounds and density, results on excess, and other quantities. More generally, these apply not only to Gabor frames, where the frame elements are simple time-frequency shifts of a given atom but also to more general systems whose elements share only general envelope of localization in the time-frequency plane.

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On PCM Quantization Error

Dr. Yang Wang

Department Of Mathematics at Georgia Institute of Technology

Abstract: A common assumption in the study of quantization errors is that the errors in different channels are independent and identically distributed. Using this assumption a Mean Square Error (MSE) estimate is derived. But is the assumption realistic? We present some theoretical studies, as well as extensive numerical data, to show that such an assumption is way off the mark. This is joint work with David Jimenez and Long Wang.

[PAPER AVAILABLE SOON]

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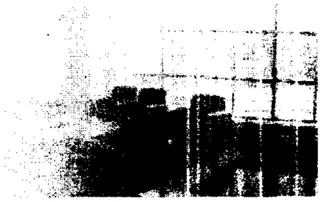

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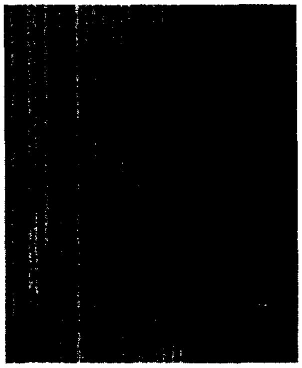

A New Encoder for Coarse Quantization of Signals

Dr. Ron DeVore

CSCAMM and Mathematics at University of Maryland

Abstract: This talk will try to understand the advantages and disadvantages of Sigma-Delta modulation from a mathematical perspective. We shall see that one of its advantages is that it is almost impervious to machine error in implementing quantization. On the other hand these methods have slow convergence compared with Pulse Code Modulation. The question arises whether we can have an encoder with the exponential convergence of PCM while retaining the error correcting of SDM. We shall describe such a class of encoders. This is joint research with Ingrid Daubechies, Sinan Güntürk and Vinay Vaishampayan.

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Unified Principle of Sigma-Delta as a Quantization Technique of Overcomplete Expansions

Dr. Thao Nguyen

Electrical Engineering at City College, CUNY

Abstract: As with the general theme of this workshop, the goal is to refine approximations of signals by coarsely quantized expansions over an overcomplete generating family of signal vectors. In this talk, we present the most abstract idea that can be extracted from the method of Sigma-Delta modulation to perform the quantization operation. The first principle implicitly introduced by Sigma-Delta modulation is to perform a change of generating family, in the same sense as "change of basis". The new family is constructed by taking each individual vector of the original family and subtracting to it a linear combination of the other generating vectors, to obtain a residual vector of reduced norm. The second principle is to quantize the expansion coefficients of the input signal with respect to the original generating family, while observing the expansion coefficients of the quantization error signal with respect to the generating family of residual vectors. Given the small norm of these vectors, the primary concern is to ensure that the latter coefficients remain bounded with reasonable bounds. Sigma-Delta modulation, the way it is commonly known, results from these abstract principles when the quantization control algorithm is restricted to be causal (one-pass) and time-invariant. This automatically implies the use of a dynamical system. Based on these abstract principles, we give an overview of the various aspects of Sigma-Delta modulation (often ignoring each other) under a unified signal-processing framework. We will show from a top-down presentation what is the position of the various research directions in Sigma-Delta modulation with respect to each other. We will include research in the context of finite and infinite dimensional signal spaces, one-dimensional and multi-dimensional signal index spaces, lowpass, bandpass and multi-channel signal expansions. With respect to the second principle, we perform a unified classification of all existing dynamical system architectures of Sigma-Delta modulation.

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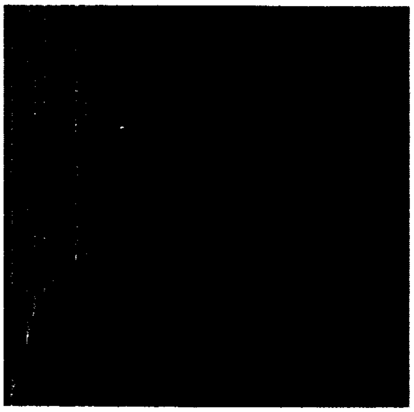

A Fast Reconstruction Method for Bandlimited Functions from its Uniform Interlaced Samples

Dr. Jared Tanner

Statistics at Stanford University

Abstract: For a number of applications it is either not possible or undesirable to acquire samples on a uniform mesh. An extension of Shannon's sampling theorem is presented in the case of uniform interleaved samples. From this extension we develop a fast O(N log N) algorithm in the case of a finite number of samples, N, are available. Moreover, by exploiting Gevrey regularity we are able to obtain precise root-exponential bounds on the convergence rate as the number of samples is increased.

[LECTURE SLIDES] [HOME PAGE]

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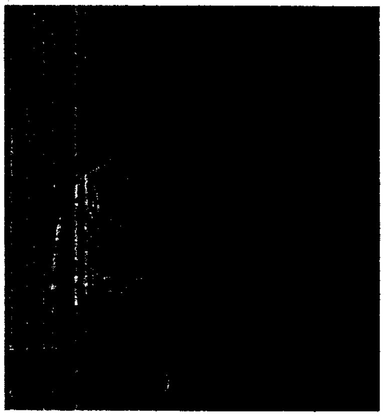

The Error Diffusion Halftoning Algorithm: Some Recent Stability Results and Applications Beyond Halftoning

Dr. Chai Wu

Thomas J. Watson Research Center at IBM

Abstract: Halftoning is the art of producing a picture which appears to have many colors using only a handful of colors. Almost all digital and analog printers use some form of halftoning; just look at any picture in a newspaper or magazine under a magnifying glass. Error diffusion is a popular technique for high quality digital halftoning. The purpose of this talk is to illustrate the versatility of error diffusion with applications beyond halftoning and to show its connection to interesting mathematical questions. I will present some recent developments in the theory and applications of error diffusion and related algorithms. In particular, I will present several stability results of error diffusion and show applications in a variety of areas besides image halftoning including online scheduling, image watermarking, steganography and data hiding, and image enhancement in twisted-nematic mode liquid crystal displays.

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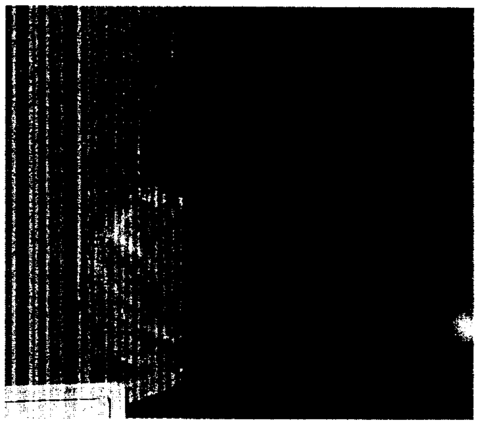

Invariant Regions for Dynamical Systems and Error Diffusion Algorithms

Dr. Mike Shub

Department Of Mathematics at University of Toronto

Abstract: We bound the accumulated error of error diffusion type algorithms by construction an invariant region for a time dependent dynamical system. This is joint work with R.Adler, B.Kitchens, M. Martens, C.Pugh and C.Tresser.

[PAPER] [HOMEPAGE]

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Progressive Halftoning by Perona-Malik Error Diffusion and Stochastic Flipping

Dr. Jackie Shen

Department of Mathematics at University of Minnesota

Abstract: Halftoning has been a significant topic in image processing due to numerous emerging applications, highly diversified approaches, and enormous challenges in theoretical analysis. Inspired by the wealthy literature on halftoning, as well as the recent PDE (partial differential equations) approach in image processing, the current work proposes a novel progressive halftoning algorithm. It is based upon the celebrated anisotropic diffusion model of Perona and Malik (*IEEE Trans. Pattern Anal. Machine Intell.*, 12:629-639, 1990), and a properly designed stochastic strategy for binary flipping. The halftone outputs from the proposed model are typical samples of some random fields, which share many virtues of successful deterministic halftone algorithms, as well as reveal many interesting features like the blue noise behavior.

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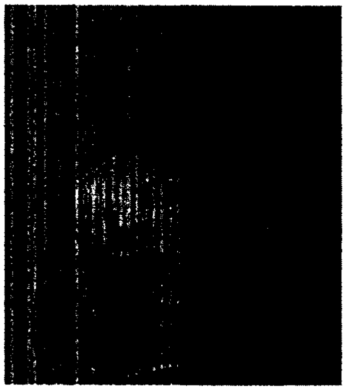

Latest Trends in Noise-Shaping from the Silicon Side

Dr. Bob Adams

Analog Devices

Abstract: Five years ago the world of noise-shaping converters was quite simple and consisted mainly of single-bit quantizers embedded in discrete-time analog loops with a filter order ranging from 2 to 8. Since then there have been significant new developments such as multi-bit quantization using so-called "Error Mismatch Shaping" techniques as well as a move towards hybrid continuous-time/discrete-time loop filters. Another trend is driven by the need to produce high-efficiency audio amplifiers using a variety of switching schemes, some of which are closely related to 1-bit delta-sigma modulators that that have been modified to minimize the number of switching transitions per unit time. Finally, I will discuss a novel approach to noise-shaping that views the problem as a direct attempt to minimize the error between a filtered version of the input signal and an identically-filtered version of a coarsely-quantized signal.

[LECTURE SLIDES]

Other presentations:
SLIDES ON: A Signal-processing Interpretation of the Riemann Zeta Function

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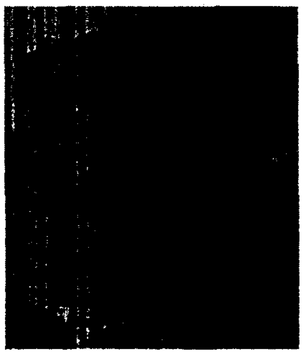

Continuous-Time Modulators for RF Applications

Dr. Joe Jensen

Ultra-High Speed Circuits Deptartment at HRL Laboratories LLC.

Abstract: We present the status and challenges of continuous-time ΣΔ modulators for RF applications. The paper includes operation principals, state-of-the-arts, and future prospects of this essential ADC technology for high-resolution and high dynamic range. Improvements in semiconductor technology and oversampled ADC converters are provide the capability to move the digitization process forward in the signal path of RF system and perform more receiver functions in the digital domain. Continuous time design approaches for oversampled ADC can provide higher frequency operation over the conventional discrete time design approaches. Tunable bandpass loop filter implementations provide the opportunity to digitize at IF or RF. We will discuss circuit design techniques for active GM-C bandpass loop filter for high dynamic range applications. Multi-bit approaches are need for wider bandwidth applications. Multi-bit noise shaped oversampled converter require techniques for feedback DAC error correction. We will show demonstrated techniques for bandpass mismatch shaping of DAC errors to reduce DAC quantization noise.

[LECTURE SLIDES]

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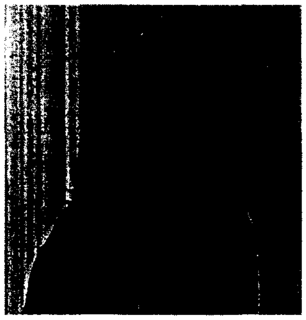

Functional Estimation for Inverse Problems

Dr. Dominique Picard

Statistics at Paris VII

Abstract: We consider the usual formulation of a statistical linear inverse problem : an unknown object of interest f is to be recovered from y" = Kf + " ˙W where y" is the observation, K is a known linear operator, and ˙W is a gaussian white noise model. The most typical example corresponds to the case where K is the convolution with a regular and known function [1]. - or, which is equivalent, to estimate the density probability of a random variable X, when we observe Z1, . . . ,Zn, iid, Zi = Xi +Ui, the Ui's are independent of the Xi's and with a fixed law.

The main difficulty lies in the fact that this problem contains two kind of bases, which are natural but may be antagonistic : the singular value decomposition basis (SVD), which allows explicit calculation and preserve the decorrelation structure of the noise (in the convolution case, it is the Fourier basis) and a basis (typically a WAVELET basis) in which one can easily express the regularity and perform Lp calculations. We provide here a method (WAVE-VD) taking advantage of both bases and allowing to directly estimate and threshold the wavelet coefficients. We show that this method achieve minimax rates of convergence in a large class of spaces, depending on the regularity of the operator K. We investigate the conditions on the operator allowing to well describe the rate of convergence of the method. We show that these conditions express in terms of sparsity of the operator, and that in the convolution case with a box-car function (I{x 2 [a, a + 1]}) these conditions express in terms of the diophantian properties of the real number a. We show that this method also allows to consider random operator K [2] and even partially observed operator.

[LECTURE SLIDES]

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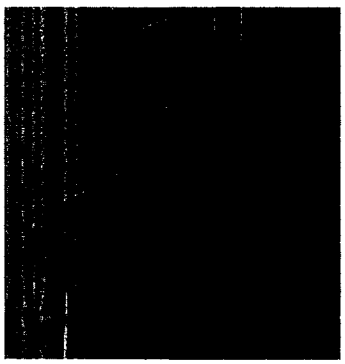
Sparse Representation in Redundant Systems

CSIC Building (#406), Seminar Room 4122.
Directions: www.cscamm.umd.edu/directions



Reconstruction of Signals: An Approach through Geometric Functional Analysis

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Abstract: How to reconstruct a signal that belongs to a small class from few linear measurements? Using methods of geometric functional analysis, we prove that for most sets of Gaussian measurements, all signals of small support can be exactly reconstructed by the L_1 norm minimization. This is an improvement of earlier results of Donoho and of Candes and Tao. This has implications in coding theory. We prove that most transform codes (linear orthogonal transformations Q from R^n into R^m) form efficient and robust robust error correcting codes. The decoder is the metric projection onto the range of Q in the L_1 norm. An equivalent problem in combinatorial geometry is the existence of a polytope with fixed number of facets and maximal number of lower-dimensional facets. We prove that most sections of the cube form such polytopes. Our work thus belongs to a common ground of coding theory, signal processing, combinatorial geometry and geometric functional analysis. This is a joint work with Mark Rudelson.

[LECTURE SLIDES]